

# DILEPTON PRODUCTION AT FERMILAB AND RHIC

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Some recent results from several fixed-target dimuon production experiments at Fermilab are presented. In particular, we discuss the use of Drell-Yan data to determine the flavor structure of the nucleon sea, as well as to deduce the energy-loss of partons traversing nuclear medium. Future dilepton experiments at RHIC could shed more light on the flavor asymmetry and possible charge-symmetry-violation of the nucleon sea. Clear evidence for scaling violation in the Drell-Yan process could also be revealed at RHIC.

## 1. Introduction

The first dilepton production experiment was performed at the AGS almost 30 years ago [1]. Over the years, hadron-induced dilepton production experiments have led to the discoveries of various vector bosons ( $J/\Psi$ ,  $\Upsilon$ , and  $Z^0$ ). They also provided important and often unique informations on parton distributions in nucleons, nuclei, and mesons.

A series of fixed-target dimuon production experiments (E772, E789, E866) have been carried out at Fermilab in the last 10 years. Some highlights from these experiments are presented here. In addition, the prospect for performing several dilepton production experiments at RHIC is discussed.

## 2. Scaling Violation in Drell-Yan Process

In the “Naive” Drell-Yan (DY) model, the differential cross section,  $m^3 d^2\sigma/dx_F dm$ , has an expression showing its scaling property as follows:

$$M^3 \frac{d^2\sigma}{dM dx_F} = \frac{8\pi\alpha^2}{9} \frac{x_1 x_2}{x_1 + x_2} \times \sum_a e_a^2 [q_a(x_1) \bar{q}_a(x_2) + \bar{q}_a(x_1) q_a(x_2)]. \quad (1)$$

The right-hand side of Eq. (1) is only a function of  $x_1, x_2$  and is independent of the beam energies. This scaling property no longer holds when QCD corrections to the DY are taken into account.

While logarithmic scaling violation is well established in Deep-Inelastic Scattering (DIS) experiments, it is not well confirmed in DY experiments at all. As an example, Figure 1 compares the NA3 data [2] at 400 GeV with the E605 [3] and E772 [4] data at 800 GeV. The solid curve in Figure 1 corresponds to NLO calculation for 800 GeV  $p + d$  ( $\sqrt{s} = 38.9$  GeV) and it describes the NA3/E605/E772 data well. No evidence for scaling violation is seen. As discussed in a recent review [5], there are mainly two reasons for this. First, unlike the DIS, the DY cross section is a convolution of two structure functions. Scaling violation implies that the structure functions rise for  $x \leq 0.1$  and drop for  $x \geq 0.1$  as  $Q^2$  increases. For proton-induced DY, one often involves a

beam quark with  $x_1 > 0.1$  and a target antiquark with  $x_2 < 0.1$ . Hence the effects of scaling violation are partially cancelled. Second, unlike the DIS, the DY experiment can only probe relatively large  $Q^2$ , namely,  $Q^2 > 16$  GeV $^2$  for a mass cut of 4 GeV. This makes it more difficult to observe the logarithmic variation of the structure functions in DY experiments.

Possible indications of scaling violation in DY process have been reported in two pion-induced experiments, E326 [6] at Fermilab and NA10 [7] at CERN. E326 collaboration compared their 225 GeV  $\pi^- + W$  DY cross sections against calculations with and without scaling violation. They observed better agreement when scaling violation is included. This analysis is subject to the uncertainties associated with the pion structure functions, as well as the nuclear effects of the  $W$  target. The NA10 collaboration measured  $\pi^- + W$  DY cross sections at three beam energies, namely, 140, 194, and 286 GeV. By checking the ratios of the cross sections at three different energies, NA10 largely avoids the uncertainty of the pion structure functions. However, the relatively small span in  $\sqrt{s}$ , together with the complication of nuclear effects, make the NA10 result less than conclusive.

RHIC provides an interesting opportunity for unambiguously establishing scaling violation in the DY process. Figure 1 shows the predictions for  $p + d$  at  $\sqrt{s} = 500$  GeV. The scaling-violation accounts for a factor of two drop in the DY cross sections when  $\sqrt{s}$  is increased from 38.9 GeV to 500 GeV. It appears quite feasible to establish scaling violation in DY with future dilepton production experiments at RHIC.

## 3. Flavor-Asymmetry and Charge-Symmetry-Violation of the Nucleon Sea

The DY process complements DIS as a tool to probe parton distributions in nucleons and nuclei. This is well illustrated in the recent progress in the study of flavor-asymmetry in the nucleon sea.

Until recently, it had been assumed that the distributions of  $\bar{u}$  and  $\bar{d}$  quarks in the proton were identical. While the equality of  $\bar{u}$  and  $\bar{d}$  is not required by any known symmetry, it is a plausible assumption for sea quarks generated by gluon splitting. As the masses of

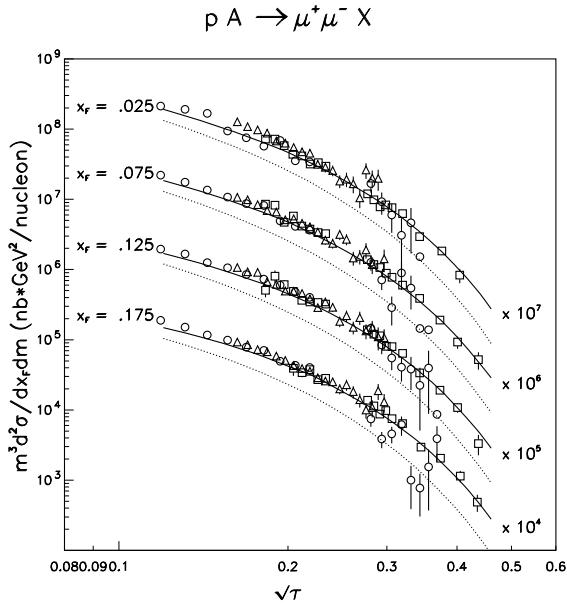


FIG. 1. Comparison of DY cross section data with NLO calculations using MRST [15] structure functions. Note that  $\tau = x_1 x_2$ . The E772 [4], E605 [3], and NA3 [2] data points are shown as circles, squares, and triangles, respectively. The solid curve corresponds to fixed-target p+d collision at 800 GeV, while the dotted curve is for p+d collision at  $\sqrt{s} = 500$  GeV.

the up and down quarks are small compared to the confinement scale, nearly equal number of up and down sea quarks should result.

The assumption of  $\bar{u}(x) = \bar{d}(x)$  can be tested by measurements of the Gottfried integral [8], defined as

$$I_G = \int_0^1 [F_2^p(x, Q^2) - F_2^n(x, Q^2)] / x \, dx = \frac{1}{3} + \frac{2}{3} \int_0^1 [\bar{u}_p(x) - \bar{d}_p(x)] \, dx, \quad (2)$$

where  $F_2^p$  and  $F_2^n$  are the proton and neutron structure functions measured in DIS experiments. The second step in Eq. 2 follows from the assumption of charge symmetry. Under the assumption of a symmetric sea,  $\bar{u}_p = \bar{d}_p$ , the Gottfried Sum Rule (GSR) [8],  $I_G = 1/3$ , is obtained.

The most accurate test of the GSR was reported by the New Muon Collaboration (NMC) [9], which measured  $F_2^p$  and  $F_2^n$  over the region  $0.004 \leq x \leq 0.8$ . They determined the Gottfried integral to be  $0.235 \pm 0.026$ , significantly below  $1/3$ . This result implies that the integral of  $\bar{d} - \bar{u}$  is nonzero. However, the  $x$ -dependence of  $\bar{d} - \bar{u}$  remained unspecified.

The proton-induced DY process provides an independent means to probe the flavor asymmetry of the nucleon sea [10]. An important advantage of the Drell-Yan process is that the  $x$ -dependence of  $\bar{d}/\bar{u}$  can be determined.

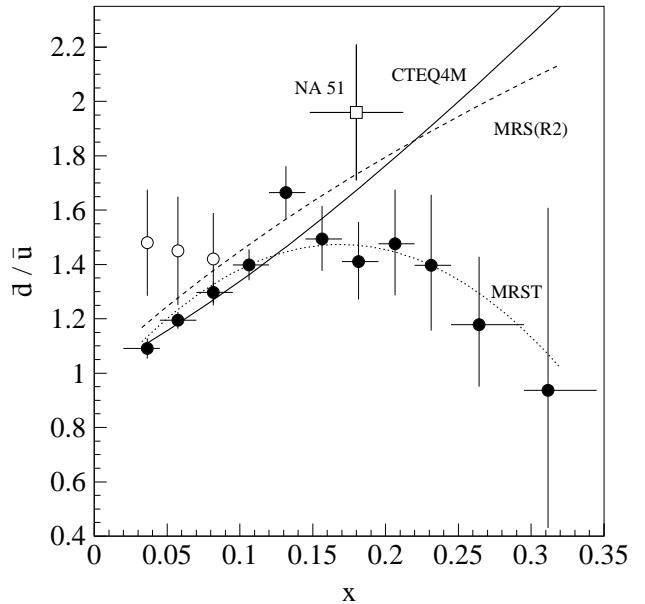


FIG. 2. The ratio of  $\bar{d}/\bar{u}$  in the proton as a function of  $x$  extracted from the Fermilab E866 cross section ratio. The curves are from various parton distributions. The error bars indicate statistical errors only. An additional systematic uncertainty of  $\pm 0.032$  is not shown. Also shown is the result from NA51, plotted as an open box. The open circles correspond to  $\bar{d}/\bar{u}$  values extracted with the assumption of the CSV effect reported in ref. [10].

The NA51 [11] and the E866 [12] collaborations have compared the proton-induced DY dimuon yields from hydrogen and deuterium targets, and they deduced the ratios of  $\bar{d}/\bar{u}$  as shown in Figure 2. For  $x < 0.15$ ,  $\bar{d}/\bar{u}$  increases linearly with  $x$  and is in good agreement with the CTEQ4M [13] and MRS(R2) [14] parameterizations. However, a distinct feature of the data, not seen in either parameterization, is the rapid decrease towards unity of  $\bar{d}/\bar{u}$  beyond  $x_2 = 0.2$ . The E866 data clearly affect the current parameterization of the nucleon sea. The most recent structure functions of Martin et al. [15] (MRST) included the E866 data in its global fit and its parametrization of  $\bar{d}/\bar{u}$  is shown in Figure 2.

Many papers have considered virtual mesons as the origin for the observed  $\bar{d}/\bar{u}$  asymmetry (see recent review of Kumano [16]). Here the  $\pi^+(\bar{d}u)$  cloud, dominant in the process,  $p \rightarrow \pi^+ n$ , leads to an excess of  $\bar{d}$  sea. Comparison of the E866 data with various theoretical models has also been made [17].

It should be emphasized that the extraction of  $\bar{d}/\bar{u}$  values from the NA51 and E866 DY experiments required the assumption of charge symmetry, namely,  $\bar{d}_n = \bar{u}_p$ ,  $\bar{u}_n = \bar{d}_p$ , etc. Evidence for a surprisingly large charge-symmetry-violation (CSV) effect was recently reported by Boros et al. [18,19] based on an analysis of  $F_2$  struc-

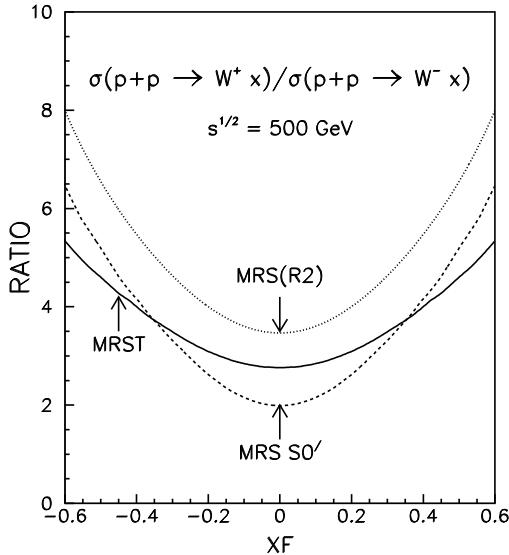


FIG. 3. Predictions of  $\sigma(p + p \rightarrow W^+ x)/\sigma(p + p \rightarrow W^- x)$  as a function of  $x_F$  at  $\sqrt{s} = 500$  GeV. The dashed curve corresponds to the  $\bar{d}/\bar{u}$  symmetric MRS S0' structure functions, while the solid and dotted curves are for the  $\bar{d}/\bar{u}$  asymmetric structure function MRST and MRS(R2), respectively.

ture functions determined from muon and neutrino DIS experiments. A large asymmetry,  $\bar{d}_n(x) \approx 1.25\bar{u}_p(x)$  for  $0.008 < x < 0.1$ , is apparently needed to bring the muon and neutrino DIS data into agreement. How would this finding, if confirmed by further studies, affect the E866 analysis of the flavor asymmetry? First, CSV alone could not account for the E866 data. In fact, an even larger amount of flavor asymmetry is required to compensate the possible CSV effect [19]. This is illustrated in Figure 2, where the open circles correspond to the  $\bar{d}/\bar{u}$  values one would have obtained if the CSV effect reported by Boros et al. is assumed. Second, there has been no indication of CSV for  $x > 0.1$ . Thus the large  $\bar{d}/\bar{u}$  asymmetry from E866 for  $x > 0.1$  is not affected.

To disentangle the  $\bar{d}/\bar{u}$  asymmetry from the possible CSV effect, one could consider  $W$  boson production, a generalized DY process, in  $p + p$  collision at RHIC. An interesting quantity to be measured is the ratio of the  $p + p \rightarrow W^+ + x$  and  $p + p \rightarrow W^- + x$  cross sections [20]. It can be shown that this ratio is very sensitive to  $\bar{d}/\bar{u}$ . An important feature of the  $W$  production asymmetry in  $p + p$  collision is that it is completely free from the assumption of charge symmetry. Figure 3 shows the predictions for  $p + p$  collision at  $\sqrt{s} = 500$  GeV. The dashed curve corresponds to the  $\bar{d}/\bar{u}$  symmetric MRS S0' [21] structure functions, while the solid and dotted curves are for the  $\bar{d}/\bar{u}$  asymmetric structure function MRST and MRS(R2), respectively. Figure 3 clearly shows that  $W$

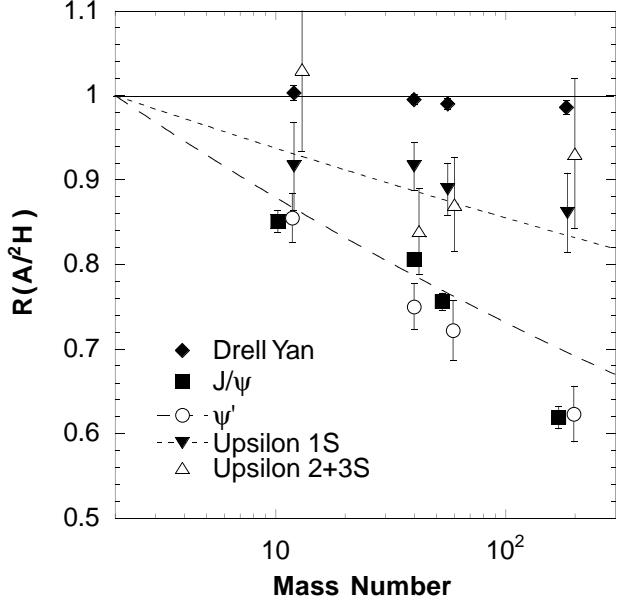


FIG. 4. Ratios of heavy-nucleus to deuterium integrated yields per nucleon for 800 GeV proton production of dimuons from the Drell-Yan process and from decays of the  $J/\psi$ ,  $\psi'$ ,  $\Upsilon(1S)$ , and  $\Upsilon(2S + 3S)$  states [5]. The short dash and long dash curves represent the approximate nuclear dependences for the  $b\bar{b}$  and  $c\bar{c}$  states,  $A^{0.96}$  and  $A^{0.92}$ , respectively.

asymmetry measurements at RHIC could provide an independent determination of  $\bar{d}/\bar{u}$ .

#### 4. Nuclear Medium Effects of Dilepton Production

From a high-statistics measurement of dilepton production in 800 GeV proton-nucleus interaction, the target-mass dependence of DY,  $J/\Psi$ ,  $\Psi'$ , and  $\Upsilon$  productions have been determined in E772 [22–24]. As shown in Figure 4, different nuclear dependences are observed for different dilepton processes. While the DY process shows almost no nuclear dependence, pronounced nuclear effects are seen for the production of heavy quarkonium states. E772 found that  $J/\Psi$  and  $\Psi'$  have similar nuclear dependence. The nuclear dependences for  $\Upsilon$ ,  $\Upsilon'$  and  $\Upsilon''$  are less than that observed for the  $J/\Psi$  and  $\Psi'$ . Within statistics, the various  $\Upsilon$  resonances also have very similar nuclear dependences.

Although the integrated DY yields in E772 show little nuclear dependence, it is instructive to examine the DY nuclear dependences on various kinematic variables. Using the simple  $A^\alpha$  expression to fit the DY nuclear dependence, the values of  $\alpha$  are shown in Figure 5 as a function of  $x_T(x_2)$ ,  $M$ ,  $x_F$ , and  $p_t$ . Several features are observed:

1. A suppression of the DY yields from heavy nuclear

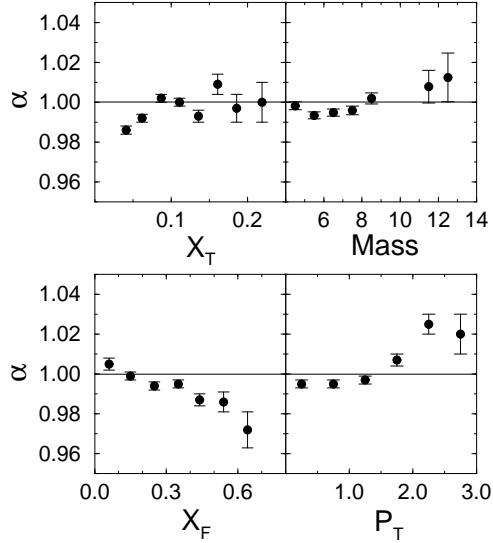


FIG. 5. Nuclear dependence coefficient  $\alpha$  for 800 GeV p+A Drell-Yan process versus various kinematic variables [22].

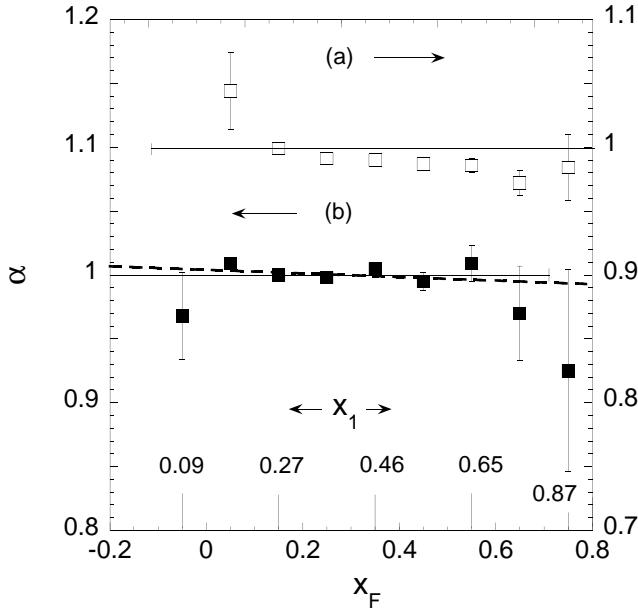


FIG. 6. Nuclear dependence coefficient  $\alpha$  for the Drell-Yan process [22] versus  $x_F$  for (a)  $x_2 \leq 0.075$ , right scale, and (b)  $x_2 \geq 0.075$ , left scale. The thin solid lines show  $\alpha = 1$ . The dashed line is a linear least-squares fit to the lower points. Also shown is the mean value of  $x_1$  for (b).

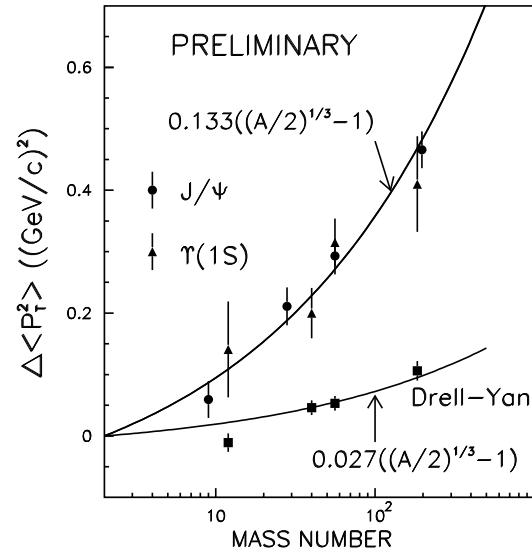


FIG. 7. The change of mean  $p_t^2$  for nuclear target,  $\Delta \langle p_t^2 \rangle = \langle p_t^2 \rangle(A) - \langle p_t^2 \rangle(D)$ , for 800 GeV p+A Drell-Yan process and  $J/\Psi$  and  $\Upsilon(1S)$  productions. The solid curves are best fits to the A-dependence of  $\Delta \langle p_t^2 \rangle$ . The  $J/\Psi$  and  $\Upsilon(1S)$  productions have identical curves for the A-dependence fits.

targets is seen at small  $x_2$ . This is consistent with the shadowing effect observed in DIS. In fact, E772 provides the only experimental evidence for shadowing in hadronic reactions. The reach of small  $x_2$  in E772 is limited by the mass cut ( $M \geq 4$  GeV) and by the relatively small center-of-mass energy (recall that  $x_1 x_2 = M^2/s$ ). p-A collisions at RHIC clearly offer the exciting opportunity to extend the study of shadowing to much smaller  $x$ .

2.  $\alpha(x_F)$  shows an interesting trend, namely, it decreases as  $x_F$  increases. It is tempting to attribute this behavior to initial-state energy-loss effect. However, there is a strong correlation between  $x_F$  and  $x_2$  ( $x_F = x_1 - x_2$ ), and it is essential to separate the  $x_F$  energy-loss effect from the  $x_2$  shadowing effect. Figure 6 shows  $\alpha$  versus  $x_F$  for two bins of  $x_2$ , one in the shadowing region ( $x_2 \leq 0.075$ ) and one outside of it ( $x_2 \geq 0.075$ ). There is no discernible  $x_F$  dependence for  $\alpha$  once one stays outside of the shadowing region. Therefore, the apparent suppression at large  $x_F$  in Figure 5 reflects the shadowing effect at small  $x_2$  rather than the energy-loss effect.

3.  $\alpha(p_t)$  shows an enhancement at large  $p_t$ . This is reminiscent of the Cronin Effect [25] where the broadening in  $p_t$  distribution is attributed to multiple parton-nucleon scatterings. It is instructive

to compare the  $p_t$  broadening for DY process and quarkonium production. Figure 7 shows  $\Delta\langle p_t^2 \rangle$ , the difference of mean  $p_t^2$  between p-A and p-D interactions, as a function of A for DY,  $J/\Psi$ , and  $\Upsilon(1S)$  productions at 800 GeV. The DY and  $\Upsilon$  data are from E772 [26], while the  $J/\Psi$  results are from E789 [27], E771 [28], and preliminary E866 analysis [29]. More details on this analysis will be presented elsewhere [26]. Figure 7 shows that  $\langle p_t^2 \rangle$  is well described by the simple expression  $a+bA^{1/3}$ . It also shows that the  $p_t$  broadening for  $J/\Psi$  is very similar to  $\Upsilon$ , but significantly larger (by a factor of 5) than the DY. A factor of 9/4 could be attributed to the color factor of the initial gluon in the quarkonium production versus the quark in the DY process. The remaining difference could come from the final-state multiple scattering effect which is absent in the DY process.

Baier et al. [30] have recently derived a relationship between the partonic energy-loss due to gluon bremsstrahlung and the mean  $p_t^2$  broadening accumulated via multiple parton-nucleon scattering:

$$-dE/dz = \frac{3}{4} \alpha_s \Delta\langle p_t^2 \rangle. \quad (3)$$

This non-intuitive result states that the total energy loss is proportional to square of the path length traversed by the incident partons. From Figure 7 and Eq. 3, we deduce that the mean total energy loss,  $\Delta E$ , for the p+W DY process is  $\approx 0.6$  GeV. Such an energy-loss is too small to cause any discernible effect in the  $x_F$  (or  $x_1$ ) nuclear dependence. As shown in Figure 6, the dashed curve corresponds to  $\Delta E = 2.0 \pm 1.7$  GeV (for p+W), and the E772 data are consistent with Eq. 3. A much more sensitive test for Eq. 3 could be done at RHIC, where the energy-loss effect is expected to be much enhanced in A-A collision [31].

- [10] S.D. Ellis and W.J. Stirling, Phys. Lett. B **256**, 258 (1991).
- [11] A. Baldit *et al.*, Phys. Lett. B **332**, 244 (1994).
- [12] E.A. Hawker *et al.*, Phys. Rev. Lett. **80**, 3715 (1998).
- [13] H.L. Lai *et al.*, Phys. Rev. D **55**, 1280 (1997).
- [14] A.D. Martin, R.G. Roberts and W.J. Stirling, Phys. Lett. B **387**, 419 (1996).
- [15] A.D. Martin *et al.*, Eur. Phys. J. C **4**, 463 (1998).
- [16] S. Kumano, Phys. Rept. **303**, 183 (1998).
- [17] J.C. Peng *et al.*, Phys. Rev. D **58**, 092004 (1998).
- [18] C. Boros, J.T. Londergan and A.W. Thomas, Phys. Rev. Lett. **81**, 4075 (1998).
- [19] C. Boros, J.T. Londergan, and Thomas AW, Phys. Rev. D **59**, 074021 (1999).
- [20] J.C. Peng, D.M. Jansen, Phys. Lett. B **354** 460 (1995).
- [21] A.D. Martin, W.J. Stirling and R.G. Roberts, Phys. Lett. B **306**, 145 (1993).
- [22] D.A. Alde *et al.*, Phys. Rev. Lett. **64**, 2479 (1990).
- [23] D.A. Alde *et al.*, Phys. Rev. Lett. **66** 133 (1991).
- [24] D.A. Alde *et al.*, Phys. Rev. Lett. **66** 2285 (1991).
- [25] J.W. Cronin *et al.*, Phys. Rev. D **11**, 3105 (1975).
- [26] P.L. McGaughey, J.M. Moss and J.C. Peng, to be published (1999).
- [27] M.H. Schub *et al.*, Phys. Rev. D **52**, 1307 (1995).
- [28] T. Alexopoulos *et al.*, Phys. Rev. D **55**, 3927 (1997).
- [29] M. J. Leitch, in Proceedings of “Quarkonium Production in Relativistic Nuclear Collisions”, Institute for Nuclear Theory, Seattle, WA, May 1998.
- [30] R. Baier *et al.*, Nucl. Phys. B **484**, 265 (1997); R. Baier *et al.*, Nucl. Phys. B **531**, 403 (1998).
- [31] R. Baier *et al.*, Nucl. Phys. B **483**, 291 (1997).

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- [1] J.H. Christenson *et al.*, Phys. Rev. Lett. **25**, 1523 (1970).
- [2] J. Badier *et al.*, Z. Phys. C **26**, 489 (1984).
- [3] G. Moreno *et al.*, Phys. Rev. D **43**, 2815 (1991).
- [4] P.L. McGaughey *et al.*, Phys. Rev. D **50**, 3038 (1994); to be published (1999).
- [5] P.L. McGaughey, J.M. Moss and J.C. Peng, hep-ph/9905409, to be published in Annu. Rev. Nucl. Part. Sci. (1999).
- [6] H.B. Greenlee *et al.*, Phys. Rev. Lett. **55**, 1555 (1985).
- [7] K. Freudenreich, Int. J. Mod. Phys. A **5**, 3643 (1990).
- [8] K. Gottfried, Phys. Rev. Lett. **18**, 1174 (1967).
- [9] P. Amaudruz *et al.*, Phys. Rev. Lett. **66**, 2712 (1991); M. Arneodo *et al.*, Phys. Rev. D **50**, R1 (1994).